Casting – Lost Wax Process

The lost wax casting process is widely used as it offers asymmetrical casting with very fine details to be manufactured relatively inexpensively. The process involves producing a metal casting using a refractory mould made from a wax replica pattern. The steps involved in the process or the lost wax casting are:

- Create a wax pattern of the missing tooth / rim
- Sprue the wax pattern
- Invest the wax pattern
- Eliminate the wax pattern by burning it (inside the furnace or in hot water). This will create a mould.
- Force molten metal into the mould - casting.
- Clean the cast.
- Remove sprue from the cast
- Finish and polish the casting on the die.

- **Defects**

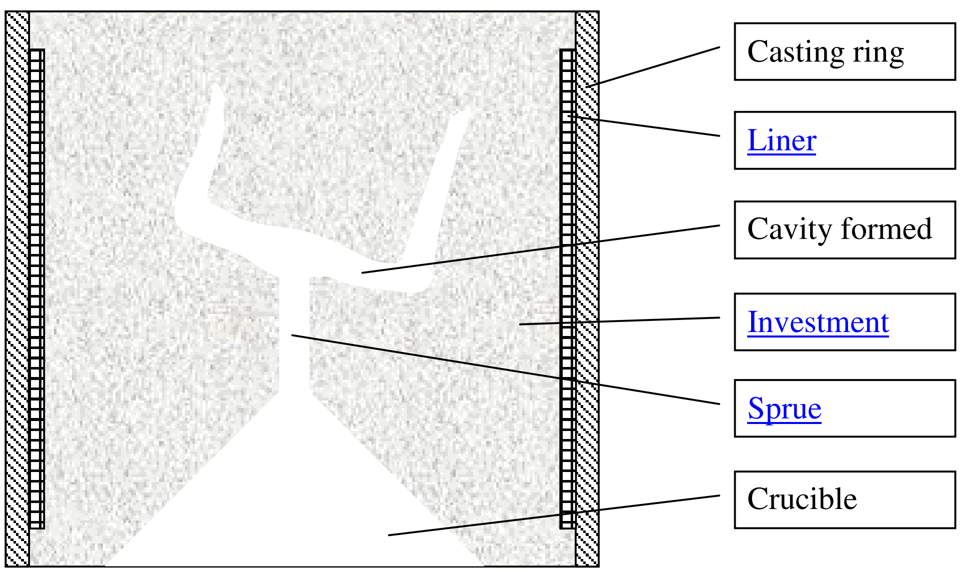

Figure 1 - depiction of a dental casting mould

A general description of the process is as given above, however it might need to be modified to account for different alloys being used. Cobalt alloys have melting temperatures between 1250 and 1450^{o}C which is higher than the investment made of gypsum decomposition temperature. Because of that, the gypsum investment must be replaced by phosphate or silica bonded type material.

The method of the alloy melting also depends on the alloy used since the temperatures required are higher than the ones which can be achieved using a torch, or the alloy can chemically react with gases.

Accuracy of this process is targeted to about 0.1%. In order to achieve this accuracy materials used in the process must be chosen as to compensate for the dimensional changes including setting shrinkage of the casting, investment shrinkage/expansion, effect of the confinement induced by the casting ring, temperature induced dimensional changes etc.

Defects in casting

The objective of the casting is to provide as accurate duplication of missing teeth as possible. However, the tolerance limits are not set exactly but generally the accuracy should be better than en be detected by the eye or conventional methods. Poor fit / accuracy of the casting could lead to fail of the restoration and lead to further dental problems.

Defects in casting can be eliminated or minimised by strict adherence to prescribed procedures. Defects in casting can generally be divided into:

- Distortion,
- Poor surface finish,
  - fins / spines
  - nodules
  - veins and ridges
  - rough surface
- Porosity,
- Voids,
- Incomplete casting.

These imperfections can be eliminated by ensuring that the common causes are minimised.

Distortion

In most cases distortion of the casting can be attributed to distortion of the wax pattern. The wax pattern distortion can be minimised by careful and proper manipulation of the wax and handling of the pattern.

In addition, some of distortion of the wax pattern can be caused by hardening of the investment around it, whereby setting and hygroscopic expansion could lead to uneven deformation of the walls of the wax pattern. This depends, on the other hand, on the type of wax, thickness and configuration of the pattern.

Poor surface finish

One of the requirements on the castings is that its surface should be as accurate reproduction of the wax pattern surface as possible. If that is not the case additional operations are required (additional finishing and polishing).

The defects under this category can be further divided in excessive surface roughness, unexpected surface irregularities and inappropriate surface colour. Surface roughness can be described as finely spaced surface imperfections, while the irregularities relate more to isolated imperfections (such as nodules). It should be accepted that the surface roughness of the casting is greater than the roughness of the wax pattern it is made of. This can be explained by a particle size of the investment which is such that it cannot reproduce the wax pattern in fine enough details.

Porosity

Porosity of the casting can be spread within the casting and on its surface. The surface porosity adds to surface roughness, but can also be a sing of the internal porosity. The internal porosity could weaken the casting, may cause discoloration if spread to the surface and in extreme cases could lead to a leakage.

Main causes of the porosity of alloy castings are:

1) Solidification defects
2) Trapped gases
3) Residual air

1 Solidification defects

Solidification defects cold lead to two different manifestations of porosity; localised shrinkage porosity and Microporosity.

Localised shrinkage porosity is caused by insufficient feeding of the alloy during solidification. As the alloy solidify, it also shrinks by over 1%, and a sufficient supply of molten alloy is required during this phase to counteract reduction in the volume caused by the shrinkage. If the sprue is not properly designed and implemented then it may solidify before the feeding is complete thus preventing a continuous supply of molten alloy. This type of defect usually occurs close to the sprue-casting junction.

Microporosity is also caused by solidification shrinkage, but generally happens in fine grain alloys when the solidification is too rapid for the microvoids to segregate. This in turn is caused the mould or casting temperature being too low.

2 Trapped gases

Many metals dissolve or occlude gases when they are molten. On solidification, these gases are forced out of the casting causing what is usually called pinhole porosity. These voids are rather small. Larger voids could be caused by the same mechanism, but could also be caused by the gases mechanically trapped within the molten alloy during the casting procedure.

3 Residual air

These voids occur on the inner surface of the casting and are caused by entrapped air which cannot escape through the investment. This can be prevented by adequate temperature during the casting, sufficiently high pressure and correct liquid – powder ratio.

Incomplete casting

If the molten alloy is prevented from fully or partially filling the mould and incomplete or even no casting at all can result. The two most obvious reasons for this are insufficient venting of the mould and high viscosity of the.

If the air in the mould could not be vented quickly once the molten allow is poured into the mould, its back pressure will prevent compete filling of the mould by the molten alloy. This point in direction of either insufficiently high casting pressure, or that it has not been applied for a sufficiently long period of time. During the early stages of the casting the metal is still quite soft, but start to solidify (and thicken) quite quickly. High casting pressure should be maintained sufficiently long after onset of solidification.

If the elimination of the wax patter was not fully complete, the pores of the investment might become filled with the combustion products thus preventing venting of the air which can cause similar issue to the above.

Common causes of defects

High heating rates

Adopting too high heating rates for the could lead to occurrence of fins (or spines) in the casting. The mechanism for this is as follows:

a) If the investment is subject to too high heating rate the outside layer becomes hot faster than the inner, and the temperature difference between the outside layer and the centre of the investment is increased.
b) Consequently, the outside layer tends to expand more than the inner parts. However, the outside layer is held back by the inner, cooler part.
c) Because of that the outside layer is subject to compressive stresses, while the inner part is subject to tensile stresses.
d) Since the investment is a brittle material, it tends to crack under tensile stresses. In this case, the most typical cracks are radial, starting from the interior of the investment and spreading outwards.
e) During casting, these cracks are filed by the casting alloy, manifesting as fins or spines.

Low temperature

Too low a temperature could cause incomplete removal of the wax. Gases, formed when the hot alloy comes in contact the residues could cause *porosity or voids* in the casting.

Too low a temperature can be caused by too short a heating time or if insufficient air is available in the furnace.

Water film

Wax is a hydrophobic material (i.e. it is repellent to water). If the investment is not in close contact with the wax pattern a water film might be formed over the surface. This water might cause occurrence of small *veins and ridges* on the surface of the casting.

Loss of contact between the investment and the wax pattern might be caused if the pattern has moved slightly, if it has been subjected to vibrations or if the painting has not been properly applied.

Air bubbles

Occasionally, small air bubbles can become attached to the pattern during or following the investing procedure. During the casting, the bubble is filled with the casting material (alloy) and is manifested as a *nodule*.

Occurrence of the air bubbles can be prevented if a vacuum investing procedure is adopted. Some other measures can be adopted to prevent this happening, too, such as use of a mechanical mixer with vibrations or application of a wetting agent in a thin layer.

Liquid – powder ratio

Both too high and too low amount of liquid could lead to a *rough surface* of the casting.

Prolonged heating

Prolonged heating at too high temperatures could lead to a disintegration of the investment with a consequence of rough mould walls. In addition, products of the disintegration could contaminate the alloy causing surface defects.

Alloy temperature

If the alloy temperature is too high it can attack the surface of the investment similar to the case of the prolonged heating. As a consequence, a similar surface roughness can occur.

Sprue

The purpose of the sprue is to provide a channel for molten alloy to reach the mould once the wax has been burnt. The sprues are generally made of wax. The diameter and the length of the sprue depend largely on the size and type of the pattern, the type of the casting machine to be used and dimensions of the ring.

Sprue diameter

The diameter of the sprue former should be approximately the same size as the thickest part of the wax pattern:

- If too large sprue is used for a particular pattern it could cause its distortion.
- If too small a sprue is attached to a rather large pattern, it could solidify before that casting causing localised imperfection - porosity.

Sprue position

It is considered that the ideal position for the sprue is at the point of the greatest bulk of the pattern (i.e. largest sectional area of the pattern), in order to avoid problems of distortion of thin patterns. Position of the sprue can also be based on the clinician's preference.

Sprue attachment

The sprue former connection to the wax pattern is generally formed in a flared shape for high density alloys, and is restricted for low density alloys. As mentioned above, the sprue should be ideally attached to the part of the pattern with the biggest cross sectional area – it is preferred for a molten alloy to flow from the thick section into the thin ones. This approach also minimises possibility for turbulence. The length of the sprue former should be long enough to locate the pattern suitably within the casting ring, sufficiently far away from the trailing surface, but not too long so not to cause too early solidification of the molten alloy.

Patterns may be sprued either directly or indirectly. For the direct spruing, there is a direct connection between the pattern and the crucible former. This way is usually used for casting of single, smaller patterns. A reservoir sphere can be added to the sprue to prevent problems with localised shrinkage in the pattern. In cases where multiple single units or fixed partial dentures are cast, the indirect spruing is adopted whereby a reservoir bar is located between the patterns and the crucible former. The volume of the reservoir should be greater than the volume of the pattern. As it is located in the centre of the heated casting ring, and because of its large volume, the reservoir should solidify last, after the pattern. Because of that, the solidification shrinkage should occur in the reservoir, and not in the pattern, see Figure 1 below.

Sprue direction

The sprue former should not be attached (as mentioned above) to any thin section of the pattern. Also, it should not be attached perpendicularly to a flat bulky part of the pattern because of a possibility of turbulence. Ideally, the sprue former should be attached at about 45° to the proximal area.

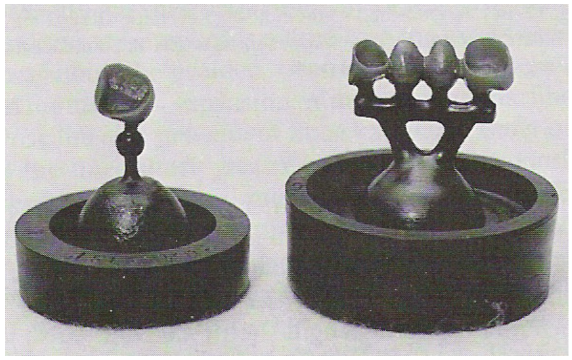

Figure 1 – Spherical reservoir on the vertical sprue (left), indirect sprue with the horizontal reservoir bar

Sprue length

The length of the sprue former is mainly governed by the length of the casting ring. If the sprue former is too short, than the pattern might be too far from the trailing end of the casting ring. In this case, gases cannot be efficiently vented from the pattern void, which could affect penetration of the molten alloy into the pattern void and cause porosity.

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Liner

Investment materials have a property of expanding on setting. If the investment was confined on the outside this could cause shrinkage of the of the mould / wax pattern. In order to prevent this effect a flexible split ring or a rubber ring could be used. However, the most commonly used technique is to line the casting ring with either an aluminosilicate liner or a cellulose liner.

The liners are cut to a proper size so that they fit into the casting ring without any overlap / gap (otherwise, a nonuniform expansion of the investment will occur). They can be used either wet or dry. If they are used wet, they should not be squeezed of excess water, as this would cause a non-uniform saturation of the liner, again leading to a non-uniform expansion of the investment. In case that more expansion is to accommodated, two layers of the liner can be used.

Sine there is less confinement of the investment in the longitudinal direction, it would tend to expand more in this direction, thus leading to a non-uniform expansion. This can be compensated if the liner is cut short and put in the casting ring so that the investment will be in contact directly with the ring at both ends. This would somewhat confine the expansion in the longitudinal direction, thus minimising the problem of non-uniform expansion.

It is to be noted that the cellulose liner (paper) is burned away during a burn-out stage which might cause the investment to fall out of the casting ring. Measures must be introduced to prevent this.

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Investment

Two types of the investments are generally used; (i) gypsum bonded and (ii) phosphate bonded. The choice of the type of the investment used depends mainly on the melting range of the alloy.

The investment is mixed in the same way as plaster or dental stone. Once mixed it is placed around the pattern and left to set. Once set, the sprue former is removed and the wax removed by the burning out process.

Gypsum based investment

The gypsum based investments have traditionally been used for casting of gold alloy inlays, onlays, crowns and fixed partial dentures.

The main constituents of the gypsum based investment are $\alpha -$hemihydrate of gypsum and quartz. The α-hemihydrate of gypsum serves as a binder and gives strength to the investment.

When heated to high temperatures, gypsum on its own shrinks and can fracture. Its change in dimension with temperature can be described as follows: it shrinks at a temperature range between 200 and 400^{o}C, it slightly expands between 400 and 700^{o}C and than it undergoes significant shrinkage beyond 700C. Because of this property, the gypsum should not be heated beyond 700C. In order to compensate for this shrinkage (which could cause the pattern void to expand) the pure gypsum moulds are significantly undersized.

Silica is added to provide a refractory component. As explained above, gypsum shrinks considerably with increase in temperature. However, if silica is added to the investment, this shrinkage can be reduced or even turned into expansion.

Setting time

The setting time of the investment is usually between 5 and 25 minutes, with the modern investments setting initially between 9 and 18 minutes.

Effects on setting expansion of the investment

- The amount of expansion of the investment is proportional to the portion of the silica component.
- It also depends on the size of the silica particles, the smaller the particles the higher the expansion.
- The higher the water/powder ratio of the investment wet mixture, the less hygroscopic setting expansion it will develop.

- The hygroscopic expansion is reduced as the mixing time is reduced.
- Duration of the immersion, especially before the initial set.
- Effect of the confinement offered by the casting ring.

Effects on thermal expansion

Thermal expansion of the investment is affected by:

- Amount and type of silica in the mixture which counterbalances shrinkage of the gypsum phase, and is in equilibrium at about 75% silica content.
- Water / Powder ratio – more water introduced in mixing leads to less thermal expansion.
- Chemical modifiers – small amounts of sodium, potassium or lithium chlorides could completely prevent any thermal shrinkage caused by the gypsum phase.
- Thermal contraction once it starts to cool down.

Phosphate based investments

The spread of use of phosphate based investment is caused by an increase in use of metal ceramic prosthesis, which require higher melting temperatures than gold alloys. These temperatures are too high to be cast adequately in the gypsum based investments. Also, use of the less expensive base metal alloys forces the use of the phosphate based investments. CP titanium and titanium alloys also require use of specially formulated investments.

The investment consists also of binders and refractory filler, which are the same as for the gypsum based investments. However, the binder in this case is magnesium oxide and a monoammonium phosphate. Carbon is also often added to the investment in order to help to produce a clean casting and to encourage easier divesting of the casting from the mould. Differently to the gypsum based investments, these investment in practice do not show signs of setting shrinkage, but rather of slight expansion.

Investing procedure

The wax patter should be thoroughly cleaned of all grease, debris etc. Any excess liquid remaining after cleaning should be shaken off and the pattern left to dry, while the investment mixture is prepared.

A required amount of the liquid (distilled water for the gypsum based investment and colloidal silica for the phosphate based investments) is poured into a clean mixing bowl, to which the powder is added gradually. Mixing should be done carefully to avoid creating any air bubbles in the wet mixture. The mixing can be done either manually, or mechanically under vacuum conditions. The latter method removes air bubbles from the mixture, and any other gasses that might be present.

Once it is mixed, it can be invested either by hand or vacuum invested.

If hand investing is chosen, the process stars with painting the entire pattern with a thin layer of the investment. After that, the casting ring is positioned on the crucible former and the rest of the investment is vibrated gently into the ring.

With the vacuum mixing and investment, the resulting casting has a smoother surface and better reproduction of small details.

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Burnout procedure

Once the investment has set for a prescribed period, the sprue former and the crucible former are carefully removed. Ideally, the investment should not be allowed to dry out before the burnout is started. There are several method of the wax burnout:

- The invested ring is placed in the furnace at a room temperature and then heated to required temperature, depending on the investment type used (higher for the phosphate based investment). The final temperature is crucial, especially for the gypsum based investments as they could decompose at too high temperatures.
- Hygroscopic low heat technique has some advantages compared to the above method in less investment degradation, smoother casting and placing the investment directly in the 500C furnace.

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Casting procedure

Once the casting temperature is reached, the casting should be made immediately, especially in case of gypsum based investments.

There are several methods for melting of alloys, which are combined with the casting methods and appropriate casting machines.:

- Torch melting,
- Electrical melting.

The natural gas/air method is the most common method for melting gold alloys as they require the maximum heat production that this method can generate. If higher temperatures are required (such as for porcelain fused to metal applications) the natural gas/ oxygen method can be applied. Even higher temperatures can be achieved by using air/acetylene or oxygen/acetylene methods, however they have some disadvantages such as:

- Excessive heat changing a composition of the alloy,
- Environmental gasses can become dissolved in the melt increasing its porosity,
- Some alloys such as base metal can be hardened and made brittle by excessive heat,
- Oxidation of the alloys can also occur due to very high temperatures.

Electrical melting can be either of the following methods:

- Resistance method, which is usually used for gold alloys. This methods offers the best control of the temperature. Electrical current is passed through a resistance heating element which causes melting of the alloy in the crucible.
- In induction melting unit the alloy is melted by an induction field generated in the crucible surrounded by water – cooled metal tubing.

- The direct current arc melting method where an arc is produced between two electrodes; the alloy and the water-cooled tungsten electrode. The temperature in the arc can reach 4000C and the melting of the alloy is very rapid.

The alloy is melted in the crucible – sprue part of the mould. The molten alloy can be forced into the mould by several methods:

- Steam pressure – which is an old method, but still in use, whereby a plug of wet asbestos is placed over the molten alloy. When it comes in contact with the molten alloy, steam is released which pushes the molten alloy into the mould.
- Pressure-vacuum casting where a vacuum is applied at the base of the mould so that the flow of the molten alloys is helped by a suction from the base.
- Pressure can also be applied to force the molten alloy into the mould. It can be preceded by evacuating the chamber first to reduce oxidation.
- Centrifugal force where a rate at which the maximum acceleration is reached is an important parameter of the casting method.

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Cleaning the cast

Once the casting has been finished, the mould is removed from the apparatus immediately. It is immersed in the cold water (quenched). Because of a sudden change in temperature and rapid steam generation, the investment breaks away from the casting. The dark surface of the casting cane be removed by a process called pickling – heating the discoloured casting in an acid until the discoloration vanishes. The pickling solution is removed by flushing it in a tap water. Polishing of the casting is the final in its preparation. Rubber, rag or felt wheels impregnated with abrasives are used in the initial phase of this stage. Final polishing is achieved using various oxides of tin and aluminium used in conjunction with a small rag or chamois buffing wheel, followed with an iron oxide rouge.

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